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SEMI-ANNUAL STATUS REPORT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Grant NGR 05-002-160*
"RESEARCH IN PARTICLES AND FIELDS"

for

1 April 1984 - 30 September 1984

E. C. Stone, Principal Investigator
L. Davis, Jr., Coinvestigator
R. A. Mewaldt, Coinvestigator
T. A. Prince, Coinvestigator

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SEMI-ANNUAL STATUS REPORT

NASA Grant NGR 05-002-160

Space Radiation Laboratory (SRL)
California Institute of Technology

1 April 1984 - 30 September 1984

This report covers the research activities in Cosmic Rays, Gamma Rays, and Astrophysical Plasmas supported under NASA Grant NGR 05-002-160. The report is divided into sections which describe the activities, followed by a bibliography.

This group's research program is directed toward the investigation of the astrophysical aspects of cosmic rays and gamma rays and of the radiation and electromagnetic field environment of the Earth and other planets. We carry out these investigations by means of energetic particle and photon detector systems flown on spacecraft and balloons.

1. Cosmic Rays and Astrophysical Plasmas

This research program is directed toward the investigation of galactic, solar, interplanetary, and planetary energetic particles and plasmas. The emphasis is on precision measurements with high resolution in charge, mass, and energy. The main efforts of this group, which are supported partially or fully by this grant, have been directed toward the following two categories of experiments.

1.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft or they complement and/or support such observations.

1.1.1. The High Energy Isotope Spectrometer Telescope (HEIST)

HEIST is a large area ($0.25 \text{ m}^2\text{sr}$) balloon-borne isotope spectrometer designed to make high-resolution measurements of isotopes in the element range from neon to nickel ($10 \leq Z \leq 28$) at energies of about 2 GeV/nucleon. The instrument consists of a stack of 12 NaI(Tl) scintillators, two Cerenkov counters (C1 and C2), and two plastic scintillators (S1 and S2) as illustrated in Figure 1. Each of the 2-cm thick NaI disks is viewed by six 1.5-inch photomultipliers whose combined outputs measure the energy deposition in that layer. In addition, the six outputs from each disk are compared to determine the position at which incident nuclei traverse each layer to an accuracy of $\sim 2 \text{ mm}$. The Cerenkov counters, which measure particle velocity, are each viewed by twelve 5-inch photomultipliers using light integration boxes. This is a collaborative effort with the Danish Space Research Institute.

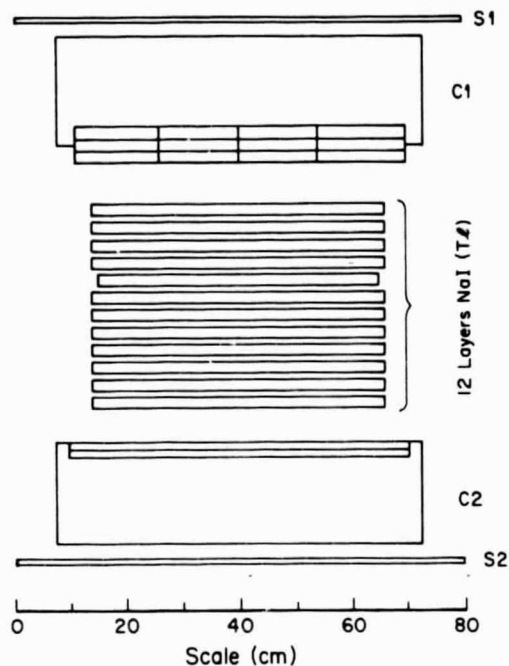


Figure 1

HEIST determines the mass of individual nuclei by measuring both the change in the Lorentz factor ($\Delta\gamma$) that results from traversing the NaI stack, and the energy loss (ΔE) in the stack. Since the total energy of an isotope is given by $E = \gamma M$, the mass M can be determined by $M = \Delta E / \Delta\gamma$. The instrument is designed to achieve a typical mass resolution of 0.2 amu.

On May 14, 1984, the HEIST instrument was launched from Palestine, Texas on its first balloon flight. It reached altitude successfully and floated over the state of Texas for approximately 38 hours at a typical atmospheric depth of $\sim 5.5 \text{ g/cm}^2$, and at geomagnetic cutoffs ranging from ~ 4.5 to 5.5 GV. During the flight more than 4×10^5 events were recorded, including $\sim 10^5$ events with charge $Z \geq 6$ and kinetic energy $E \geq 1.4 \text{ GeV/nucleon}$. Although only a subset of these are suitable for isotope analysis, the others are being used for in-flight mapping and stability checks.

Except for minor malfunctions, HEIST operated perfectly during the flight. Preliminary analysis of the data has shown that all of the 108 phototubes operated as expected, and that their outputs were stable to $\leq 5\%$ over the course of the flight. It is likely that they were stable to much better than this ($\leq 1\%$), since the automatic evaporative-cooling system was able to maintain the internal temperature of the

gondola (in the region of the NaI stack) to 25 ± 0.5 °C over the entire float period, about an order of magnitude better temperature stability than in typical balloon-flight systems. This will minimize the need for corrections for any temperature-dependent variations in the gains of the various detector electronics, or in the NaI light output.

The first data analysis objectives will be to obtain detailed maps of the response of the each PMT viewing the NaI crystals, and also maps of the ratio of the response of various tubes. These maps are used to derive the energy loss of each event in each of the crystals, and to determine the trajectory of each event through the NaI stack and the Cerenkov counters. Earlier analysis, confined to limited regions of the counters, showed that within a given NaI layer it is possible to measure the position to ~ 1.3 mm and the energy loss to an accuracy of $\sim 1\%$ for ^{55}Mn ions. The ^{55}Mn Bevalac calibration data are now being analysed to map the entire area of the crystals. Preliminary results indicate that there is no serious degradation of the response near the outer edges of the disks.

Copies of the data tapes have also been shipped to our collaborators at the Danish Space Research Institute, where they will focus their efforts on mapping and calibration of the response of the Cerenkov counters.

1.1.2. Low Energy Isotope Spectroscopy

In August of 1984 we completed a successful calibration of solid-state detectors at the Lawrence Berkeley Laboratory Bevalac, in which we studied several problems important to isotope spectrometers based on silicon solid-state detectors. In particular, we investigated a "charge multiplication" problem that has plagued several thin (~ 30 to 150 μ) solid-state detectors flown on previous missions. The characteristic of this phenomenon is that the signal from a significant fraction of the particles that lose a great deal of energy in the detector (e.g., stopping Fe ions) is measured to be ~ 20 to 30% greater than expected, with greatly degraded resolution. At Berkeley we tested a detector from ORTEC that had received special manufacturing treatments designed to eliminate this problem. Preliminary analysis indicates at least an order of magnitude reduction in the fraction of events exhibiting this problem.

Other areas of investigation during this calibration were an extension of our mass spectroscopy capabilities up to Kr ($Z=36$) isotopes, further calibrations of position-sensitive solid-state detectors, and further work on determining cosmic ray fragmentation cross sections at low energies. These data are now being analysed.

1.2. Experiments on NASA Spacecraft

The SR&T grant program of the Space Radiation Laboratory is strengthened by and contributes to the other programs described here. Activities related to these programs are primarily funded by mission-related contracts but grant funds are used to provide a general support base and the facilities which make these programs possible.

1.2.1. An Electron/Isotope Spectrometer (EIS) Launched on IMP-7 on 22 September 1972 and on IMP-8 on 26 October 1973

This experiment is designed to measure the energy spectra of electrons and positrons (0.16 to ~6 MeV), and the differential energy spectra of the nuclear isotopes of hydrogen, helium, lithium, and beryllium (~2 to 50 MeV/nucleon). In addition, it provides measurements of the fluxes of the isotopes of carbon, nitrogen, and oxygen from ~5 to ~15 MeV/nucleon. The measurements from this experiment support studies of the origin, propagation, and solar modulation of galactic cosmic rays; the acceleration and propagation of solar flare and interplanetary particles; and the origin and transport of energetic magnetospheric particles observed in the plasma sheet, adjacent to the magnetopause, and upstream of the bow shock.

The extensive EIS data set has been utilized in comprehensive studies of solar, interplanetary, and magnetospheric processes. Correlative studies have involved data from other IMP investigations and from other spacecraft, as well as direct comparisons of EIS data from IMP-7 and IMP-8. In particular, we are currently using IMP data to support a multidisciplinary workshop that is studying cosmic ray modulation and the large scale structure of the heliosphere.

The following papers based on IMP data have recently been published:

- "Microstructure of Magnetic Reconnection in Earth's Magnetotail," J. W. Bieber et al., *J. Geophys. Res.* **89**, 6705 (1984).
- "The Isotopic Composition of the Anomalous Low-Energy Cosmic Rays," R.A. Mewaldt et al., *Ap. J.* **283**, 450 (1984).

1.2.2. An Interstellar Cosmic Ray and Planetary Magnetospheres Experiment for the Voyager Missions Launched in 1977.

This experiment is conducted by this group in collaboration with F. B. McDonald and J. H. Trainor (Goddard Space Flight Center), W. R. Webber (University of New Hampshire), and J. R. Jokipii (University of Arizona), and has been designated the Cosmic Ray Subsystem (CRS) for the Voyager Missions. The experiment is designed to measure the energy spectra, elemental and (for lighter elements) isotopic composition, and streaming patterns of cosmic-ray nuclei from H to Fe over an energy range of 0.5 to 500 MeV/nucleon and the energy spectra of electrons with 3 - 100 MeV. These measurements will be of particular importance to studies of stellar nucleosynthesis, and of the origin, acceleration, and interstellar propagation of cosmic rays. Measurements of the energy spectra and composition of energetic particles trapped in the magnetospheres of the outer planets are used to study their origin and relationship to other physical phenomena and parameters of those planets. Measurements of the intensity and directional characteristics of solar and galactic energetic particles as a function of the heliocentric distance will be used for *in situ* studies of the interplanetary medium and its boundary with the interstellar medium. Measurements of solar energetic particles are crucial to understanding solar composition and solar acceleration processes.

The CRS flight units on both Voyager spacecraft have been operating successfully since the launches on August 20, 1977 and September 5, 1977. The CRS team participated in the Voyager 1 and 2 Jupiter encounter operations in March and July 1979, and in the Voyager 1 and 2 Saturn encounters in November 1980 and August 1981. The Voyager data represent an immense and diverse data base, and a number

of scientific problems are under analysis. These investigation topics range from the study of galactic particles to particle acceleration phenomena in the interplanetary medium, to plasma/field energetic particle interactions, to acceleration processes on the sun, to studies of elemental abundances of solar, planetary, interplanetary, and galactic energetic particles, and to studies of particle/field/satellite interactions in the magnetospheres of Jupiter and Saturn.

The following publications and papers for scientific meetings, based on Voyager data, were generated:

- "Elemental Composition of Solar Energetic Particles," W.R. Cook et al., *Ap. J.* **279**, 827-838 (1984).
- "The Voyager Mission: Encounters with Saturn," E.C. Stone, *J. Geophys. Res.* **88**, 8369 (1983).
- "Voyager Measurements of the Energy Spectrum, Charge Composition, and Long Term Temporal Variations of the Anomalous Components in 1977-1982," W. R. Webber and A. C. Cummings, *Proceedings of Solar Wind V Conference, NASA CP 2280*, 427-434 (1983).
- "Temporal Variations of the Anomalous Oxygen Component," A. C. Cummings and W. R. Webber, *Proceedings of Solar Wind V Conference, NASA CP 2280*, 435-440 (1983).
- "The Saturn System," E.C. Stone and T. Owen, *Saturn* (Submitted for 1984).
- "Evidence that the Anomalous Component is Singly Ionized," A. C. Cummings et al., *Ap. J. In Press*.

1.2.3. A Heavy Isotope Spectrometer Telescope (HIST) Launched on ISEE-3 in August 1978

HIST is designed to measure the isotope abundances and energy spectra of solar and galactic cosmic rays for all elements from lithium to nickel ($3 \leq Z \leq 28$) over an energy range from several MeV/nucleon to several hundred MeV/nucleon. Such measurements are of importance to the study of the isotopic constitution of solar matter and of cosmic ray sources, the study of nucleosynthesis, questions of solar-system origin, studies of acceleration processes and studies of the life history of cosmic rays in the galaxy.

HIST was successfully launched on ISEE-3 and provided high resolution measurements of solar and galactic cosmic ray isotopes until December 1978, when a component failure reduced its isotope resolution capability. Since that time, the instrument has been operating as an element spectrometer for solar flare and interplanetary particle studies.

Our work on solar flare, interplanetary, and galactic cosmic ray isotopes has resulted in the following recent papers.

- "A High Resolution Study of the Isotopes of Solar Flare Nuclei," R. A. Mewaldt et al., *Ap. J.* **280**, 892 (1984).

- "An Accelerator-Test of Semi-Empirical Cross-Sections," K.H. Lau et al., *Proceedings of 18th International Cosmic Ray Conference, Bangalore, India* 9, 255 (1983).
- "The Isotopic Composition of the Anomalous Low-Energy Cosmic Rays," R.A. Mewaldt et al., *Ap. J.* 283, 450 (1984).

1.2.4. A Heavy Nuclei Experiment (HNE) Launched on HEAO-C in September 1979

The Heavy Nuclei Experiment is a joint experiment involving this group and M. H. Israel, J. Klarmann, W. R. Binns (Washington University) and C. J. Waddington (University of Minnesota). HNE is designed to measure the elemental abundances of relativistic high-Z cosmic ray nuclei ($17 \leq Z \leq 130$). The results of such measurements are of significance to the studies of nucleosynthesis and stellar structures, the existence of extreme transuranic nuclei, the origin of cosmic rays, and the physical properties of the interstellar medium. HNE was successfully launched on HEAO-3 and operated until gyro failure in late May 1981.

The following talks and papers were presented during the reporting period:

- "Elemental Abundances of Ultraheavy Cosmic Rays," W.R. Binns et al., *COSPAR Symposium on Nucleosynthesis & Acceleration of Cosmic Rays*.
- "HEAO-3 Observations on Nuclei of Platinum and Lead in the Cosmic Radiation," D.J. Fixsen et al., *Bull. of Amer. Phys. Soc.* 29, 735 (1984).
- "Rigidity Spectra of Ultraheavy Cosmic Ray Results from HEAO-3," M.D. Jones et al., *Bull. Am. Phys. Soc.* 29, 735 (1984).
- "Elemental Abundances for Cosmic Rays with $26 \leq Z \leq 42$: HEAO-3 Results," W.R. Binns et al., *Bull. Am. Phys. Soc.* 29, 734 (1984).

In addition the late volumes for the 18th ICRC appeared so that publication data is available for those papers - see the bibliography.

1.2.5. A Magnetometer Experiment on Pioneer 11

The Pioneer 11 Vector Helium Magnetometer Experiment is a joint investigation involving several research centers, with E. J. Smith (JPL) as Principal Investigator and Leverett Davis, Jr. (SRL) as the Caltech Co-Investigator.

Pioneer 11 is a spinning spacecraft whose roll axis is directed toward the earth. Normally its roll attitude was determined by observations of the sun. But at the time of the Saturn encounter the sun was nearly in line with the earth and the usual procedure could not be used to accurately determine the roll attitude. Instead, this was done using data from the Imaging Photopolarimeter supplied by Gehrels and Doose. A paper by Connerney, Acuña, and Ness, *J. Geophys. Res.* 89, 7541-7544, 1984, pointed out that their Z_9 model would fit the observations better if the roll attitude were changed by $1^\circ 4'$ during the entire period when Pioneer was within 8 Saturn radii ($8 R_s$) of the planet. They speculated that this might be due to an uncertainty of the

orientation of the magnetometer on the spacecraft, or to a phase lag in the instrumental electronics, or to an uncertainty in the spacecraft roll orientation.

We then obtained from Dose and Gehrels more accurate data on the roll attitude that had not been available previously. The required roll attitude correction varied with time in an irregular way between $-0^{\circ}13$ and $1^{\circ}34$. Using these corrections to the Vector Helium Magnetometer data, we derived a new, completely axisymmetric spherical harmonic model, labeled the P_{1184} model, of Saturn's magnetic field inside $8 R_s$ of the planet that in this range had a weighted root mean square percent residual of 1.13%, and for data inside $3 R_s$, a percent residual of 0.40%. The internal source harmonic coefficients are $g_1^0 = .2114$, $g_2^0 = .0160$, $g_3^0 = .0226$ Gauss, and the external source coefficient, G_1^0 , is -7.1 nT while Pioneer is inbound and is -12.6 nT outbound after occultation. This change is due to a change in the currents in the bow shock, the magnetopause, and the ring current system suggested by Connerney et al. For the Z_3 model of Connerney, Ness, and Acuña, *Nature*, **295**, 44-46, 1982, the corresponding root mean square weighted percent residuals are 1.81% inside $8 R_s$ and 1.02% inside $3 R_s$.

We believe that both the P_{1184} model and the Z_3 model fit the Pioneer 11 Vector Helium Magnetometer roll corrected data very well but that our P_{1184} model provides a definitely better fit.

Publications.

*"Magnetic Field Models," Connerney, J.E.P., L. Davis, Jr., and D. L. Chenette, *Saturn*, ed. by T. Gehrels and M. S. Matthews, University of Arizona Press, 354-377, 1984.

*"Comments on the Paper 'The Z_3 Model of Saturn's Magnetic Field and the Pioneer 11 Vector Helium Magnetometer Observations' by Connerney, Acuña, and Ness," Davis, L., Jr. and E. J. Smith, *J. Geophys. Res.* (in press 1985).

1.2.6. Proposal for an Advanced Composition Explorer (ACE)

This investigation proposed jointly by this group, and by W. D. Arnett and J. A. Simpson (University of Chicago), L. F. Burlaga (GSFC), R. E. Gold and S. M. Krimigis (APL/JHU), W. C. Feldman (LANL), G. Gloeckler and G. M. Mason (UMd), and J. V. Hollweg (UNH), is for the study of an Advanced Composition Explorer (ACE). This Explorer-class mission would make comprehensive measurements of the elemental and isotopic composition of accelerated nuclei with increased sensitivity of several orders of magnitude, and with improved mass and charge resolution. ACE would observe particles of solar, interplanetary, and galactic origins, spanning the energy range from that of the solar wind (~ 1 keV/nucleon) to galactic cosmic ray energies (several hundred MeV/nucleon). Definitive studies would be made of the abundance of essentially all isotopes from H to Zn ($1 \leq Z \leq 30$), with exploratory isotope studies extending to Zr ($Z=40$), and element studies extending to U ($Z=92$).

ACE would be a coordinated experimental and theoretical effort, designed to investigate a wide range of fundamental problems. In particular, ACE would provide the first extensive tabulation of solar isotopic abundances based on direct sampling of solar material and would establish the pattern of isotopic differences between galactic cosmic ray and solar system matter. These composition data would be used to investigate basic dynamical processes that include the formation of the solar corona, the acceleration of the solar wind, and the acceleration and propagation of energetic nuclei on the Sun, in interplanetary space, and in cosmic ray sources. They would also be used to study the history of solar system material and of galactic cosmic ray material, and to investigate the differences in their origin and evolution.

The ACE study payload includes four high resolution spectrometers, each designed to provide the ultimate charge and mass resolution in its particular energy range, and each having a collecting power 1 to 3 orders of magnitude greater than previous or planned experiments. Included in the study would be two spectrometers, a Solar Isotope Spectrometer (SIS) and a Cosmic Ray Isotope Spectrometer (CRIS), for which Caltech would play a leading role. These spectrometers would make use of the proven mass-resolution techniques and large-area detectors that were developed and tested by this laboratory over the past decade, partly through the support of this grant.

1.2.7. Galileo Heavy Ion Counter

This experiment, being constructed by this group in collaboration with N. Gehrels at Goddard Space Flight Center, is being added to the Galileo mission as an engineering subsystem. It will monitor penetrating (~ 10 to ~ 200 MeV/nucleon) sulfur, oxygen, and other heavy elements in the Jovian magnetosphere with the sensitivity needed to warn of potential "single-event upsets" (SEU) in the attitude control system computer. (SEUs are state changes induced by ionizing radiation.) Caltech is responsible for management, detector testing, and calibration of the experiment, which is based on repackaging the Voyager CRS prototype unit (the PTM). Although the primary purpose is engineering support, the data will allow us to continue our investigation of spectra of trapped ions in the Jovian magnetosphere and their relation to the Jovian aurora. In addition, during cruise phase and in the outer Jovian magnetosphere, we will use the instrument to measure the elemental composition of solar flare events and of the anomalous cosmic ray component, beginning in 1986 and continuing through ~ 1991 .

2. Gamma Rays

This research program, which has received significant support from Caltech, is directed toward the investigation of galactic, extragalactic, and solar gamma rays with spectrometers of high angular resolution and moderate energy resolution carried on spacecraft and balloons. The main efforts have been directed toward the following two categories of experiments.

2.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft and they complement and/or support such experiments.

2.1.1. A Balloon-Borne Gamma Ray Imaging Payload (GRIP)

The principal focus of our current gamma-ray astronomy effort is the construction of a balloon-borne imaging gamma-ray telescope for galactic and extragalactic astronomy observations. A shielded NaI Anger camera will be used in combination with a 2-cm thick, lead, rotating, coded-aperture mask to achieve an imaging capability of 1000 0.6° pixels in a 20° field of view and a localization capability of 3 arc minutes for 10σ sources. This performance represents more than an order of magnitude improvement over previous balloon and satellite instrumentation. The $16'' \times 2''$ NaI Anger camera plate will have an energy range of 30 keV to 3 MeV and achieve a continuum sensitivity of $6 \times 10^{-7} / \text{cm}^2 \text{ s keV}$ at 1 MeV.

The status of the various instrument subsystems is as follows:

- Anger Camera: Assembled and mapped. Refinement of position determination algorithms in progress.
- Shield System: Plastic shield and NaI shield segments assembled and tested. Shield PMT's assembled and tested.
- Analog Electronics: Anger camera flight ADC's fabricated. Shield discriminator and trigger circuitry fabricated.
- Digital Electronics: Event logic fabricated. Microprocessor readout system operational and interfaced with PDP 11/24 GSE.
- Data Recording System: Video cassette recorders and PCM unit procured. Flight video readout and PDP 11/24 1 Mbit/s video interface in fabrication.
- Coded Aperture Mask: Mask rotation stage fabricated. Individual lead/tin mask elements fabricated and ready for mounting on mask support plate.
- Telescope Mechanical System: Shield and Anger camera support frame fabricated and mechanically integrated with detectors. Mask tower, shell, and shell domes fabricated. Laboratory handling fixtures fabricated.
- Pointing System and Gondola: Azimuthal torquer fabricated. Pointing platform designed and materials acquisition in progress. Pointing aspect sensors defined and in process of procurement.

The telescope mechanical integration is to take place in December, 1984. The integration of the telescope and pointing platform is scheduled for February, 1985. First flight of telescope should occur during the fall turnaround in 1985.

The instrument technique has been described in:

- "Gamma-Ray Imaging with a Rotating Hexagonal Uniformly Redundant Array," W. R. Cook et al., *IEEE Trans. Nuclear Sci.* NS-31, 771-775 (1984).
- "A Thick Anger Camera for Gamma-Ray Astronomy," W. R. Cook et al., Paper presented at IEEE Nuclear Science Symposium, Oct. 1984 (1984).

2.2. Experiments on NASA Spacecraft

The scientific vitality of the SRL gamma ray program is enhanced by collaboration in the analysis of gamma ray data from recent missions. This analysis effort is carried out on the SRL data analysis system.

2.2.1. The Gamma Ray Spectrometer Experiment on the Solar Maximum Mission (SMM)

The Solar Maximum Mission satellite was launched in early 1980 and has been in continuous operation observing gamma-ray emission from solar flares. The University of New Hampshire instrument is sensitive to photons in the energy range 0.3-100 MeV, and can also detect energetic neutrons above 40 MeV.

We have collaborated with U.N.H. in the study of 2.22 MeV emission from neutron capture on hydrogen, following up on our earlier work with the HEAO-3 spacecraft. The focus of the SMM data analysis has been a study of 2.22 MeV line emission in a sample of 8 flares, which includes the very intense solar flare of 3 June 1982. The data from these flares have allowed a detailed study of the time history of the 2.22 MeV neutron capture line from which conclusions have been drawn concerning the production of low energy neutrons in solar flares, the density at which neutrons are captured, and the ^3He abundance in the photosphere.

The following invited talk was presented in connection with this work:

- "Gamma-Ray and Neutron Emission from Flares," T. A. Prince, *Bull. Am. Astro. Soc.* 16, 511.

3. Other Activities

R. A. Mewaldt is serving as a member of the High Energy Astrophysics Management Operations Working Group (HEAMOWG), the Cosmic Ray Program Working Group (CRPWG), and as the "OG" program chairman for the 19th International Cosmic Ray Conference.

T. A. Prince has received a Presidential Young Investigator Award from the National Science Foundation.

E. C. Stone continues to serve as NASA's Project Scientist for the Voyager Mission. He is also a member of the Space Science Board, the NASA University Relations Study Group, and the steering group of the SSB study, "Major Directions for Space Science: 1995-2015".

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- "HEAO-3 Observations on Nuclei of Platinum and Lead in the Cosmic Radiation," Fixsen, D.J. et al., *Bull. of Amer. Phys. Soc.* **29**, 735 (1984).
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